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The importance of the fibre tracts connecting the planum temporale in absolute pitch possessors

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ABSTRACT

In the present study we investigated 90 musicians of both sexes who possess different degrees of absolute pitch (AP) using diffusion tensor imaging in association with a correlational approach and evaluated whether there are differences in perisylvian connections depending on the proficiency level of AP. We expected higher fractional anisotropy with increasing AP ability in the white matter underlying perisylvian brain areas. Results revealed a significant positive correlation between the proficiency level of AP and fractional anisotropy values in the left-sided white matter underlying the planum temporale. We interpret this result as an indicator of auditory processing differences between musicians possessing different degrees of AP, reflecting early auditory encoding and categorization processes. The present study provides further evidence for the substantial importance of the left-sided planum temporale for the ability of AP.

1. Introduction

People with normal hearing abilities are usually able to recognize whether a perceived tone is higher, lower, quieter, or louder compared to another tone that occurs in sufficient temporal nearness. However, some people are able to classify pitches absolutely into tone categories without the use of a reference tone (Bachem, 1937). This relatively rare ability is called absolute pitch (AP). So far, a vast range of AP abilities has been described in previous studies ranging from excellent to random performance with many intermediate levels (Bachem, 1937; Ward et al., 1982). Since a partial AP ability occurs more frequently than a perfect or no AP ability (Wengenroth et al., 2014), many authors have suggested that the ability of AP is gradually distributed rather than being an all-or-nothing phenomenon (Bermudez and Zatorre, 2009; Itoh et al., 2005; Wilson et al., 2009). However, the neurophysiological and cognitive underpinnings of AP are not entirely understood. In fact, it is still a matter of debate whether early perceptual processes (Burkhard et al., 2019; Hirata et al., 1999; Schulze et al., 2009; Wengenroth et al., 2014) or later cognitive processing stages determine AP (Elmer et al., 2013; Levitin and Rogers, 2005; Zatorre, 2003). The latter are thought to be mostly modulated by frontal brain regions, whereas the former are dependent upon perisylvian areas. In this study, we focused on white matter (WM) underlying perisylvian brain areas, which are thought to be important for perception, encoding, and categorization of tonal information at the initial stage of auditory processing (Schulze et al., 2009; Wengenroth et al., 2014).

One of the most discussed perisylvian brain regions subserving AP is the planum temporale (PT), which is involved in auditory processing and supports categorical perception (Griffiths and Warren, 2002; Schlaug et al., 1995). Several studies reported an atypically strong left-sided PT anatomical asymmetry in AP musicians, its cause is discussed controversially in the existing literature (Griffiths and Warren, 2002; Keenan et al., 2001; Schlaug et al., 1995). Whether this well-documented strong left-sided PT asymmetry might be related to the also reported strong right-sided anatomical asymmetry of Heschl's gyrus (HG) is currently not clear. Nevertheless, these studies document an atypical anatomical of the perisylvian brain. In addition, several studies reported positive correlations between pitch labeling abilities and left-sided PT activation (Wilson et al., 2009; Zatorre et al., 1998). Connectivity studies also showed atypical connectivity patterns in AP compared to relative pitch (RP) musicians. Studies applying diffusion tensor imaging (DTI) protocols found increased fractional anisotropy (FA) values in absolute pitch

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possessors (APPs) (Dohn et al., 2015; Loui et al., 2011; Oechslin et al., 2010), which are often interpreted as indicators of increased anatomical connectivities. Loui et al. (2011) revealed increased volumes of WM tracts connecting the posterior superior temporal gyrus (pSTG) with the ipsilateral posterior middle temporal gyrus (pMTG) for APPs compared to non-APPs, whereby AP performance was predicted by the left-sided tract volume. Moreover, the pSTG as well as the pMTG, are connected to the inferior frontal gyrus through the arcuate fasciculus (Catani et al., 2005), which is part of the superior longitudinal fasciculus (SLF). A previous study showed increased connectivity in the left SLF with higher FA for APPs (Oechslin et al., 2010). Furthermore, Kim and Knösche (2016) revealed enhanced intracortical myelination in the right planum polare (PP) for APPs compared to non-APPs.

To emphasize the gradual nature of the AP ability, 90 professional musicians were investigated using a correlational approach. Relationships between the proficiency level of AP and perisylvian WM were assessed using a pitch-labeling score and FA as a measure of WM integrity. Based on the existing literature (Dohn et al., 2015; Loui et al., 2011; Oechslin et al., 2010), we expected that musicians with higher AP proficiency will show increased FA compared to musicians with lower AP proficiency. To our knowledge, this is the first study that investigates FA of APPs by taking into account AP ability as a continuous measure instead of using arbitrary group classifications.

2. Materials and methods

2.1. Participants

The participants of this study already participated in a recently published electroencephalography (EEG) study of our group (Burkhard et al., 2019). Based on the fact that AP faculty is considered as a continuous rather than a dichotomous ability (Bermudez et al., 2009; Itoh et al., 2005; Levitin and Rogers, 2005; Wilson et al., 2009), DTI data of 103 highly trained musicians with different levels of AP performance were acquired (Table 2). Participants were recruited from music conservatories and orchestras and all were either professional musicians, music students, or highly-trained amateur musicians. Since in the former EEG study nine subjects had to be excluded due to drug abuse and/or psychiatric disorders (depression and anxiety), these participants were also excluded from DTI analyses. Four additional participants had to be excluded because no DTI data were available, resulting in a total sample size of 90 subjects. All participants gave written informed consent, were paid for their participation and the study procedures were in accordance with the Declaration of Helsinki and the Ethics Commission of the University of Zurich approved the study.

AP ability was tested with a modified version of an in-house AP test (Oechslin et al., 2010) that was administered at home by the participants. During this test, the participants had to label 108 sine tones ranging from C3 to B5 (A4 = 440 Hz) that were presented in a pseudo-randomized order. The pitch-labeling score was defined as the percentage of correct responses. A trial was counted as correct if the exact pitch chroma was identified. Errors in pitch height were neglected because previous studies showed that AP musicians make octave judgment errors occasionally (Miyazaki, 1989). As depicted in Fig. 1, AP test performance of the subjects varied from random to perfect.

Musical expertise was assessed using in-house questionnaires, whereas handedness was measured using the Annett questionnaire (Annett, 1970). General cognitive ability was surveyed using a German intelligence test (KAI: Kurztest für allgemeine Intelligence (Lehrl et al., 1992). Furthermore, the stabilized musical aptitude of the participants was evaluated using the Advanced Measures of Music Audition (AMMA) test (Gordon, 1989). This test enables to evaluate the ability to discriminate two given melodies by their rhythmic or tonal properties. The test was designed to evaluate musical aptitude regardless of musical achievement. According to pure-tone audiometry, all participants demonstrated a normal audiological status (MAICO Diagnostic GmbH, Berlin, Germany).

2.2. DTI data acquisition and preprocessing

MRI data were acquired on a 3T Philips Ingenia scanner (Philips Medical Systems, Best, The Netherlands) using a 15-channel head coil. Single-shot spin-echo echo-planar imaging along 64 different geometrical directions was applied to obtain diffusion-weighted images with a b-value of 1000 s/mm^2 and one reference volume (non-diffusion-weighted). Further scan parameters were echo time = 89 ms, repetition time = 10,022 ms, flip-angle $\alpha = 90^{\circ}$, echo-planar imaging factor = 55, sensitivity encoding factor = 2, field of view = 224 × 224 mm^2, voxel

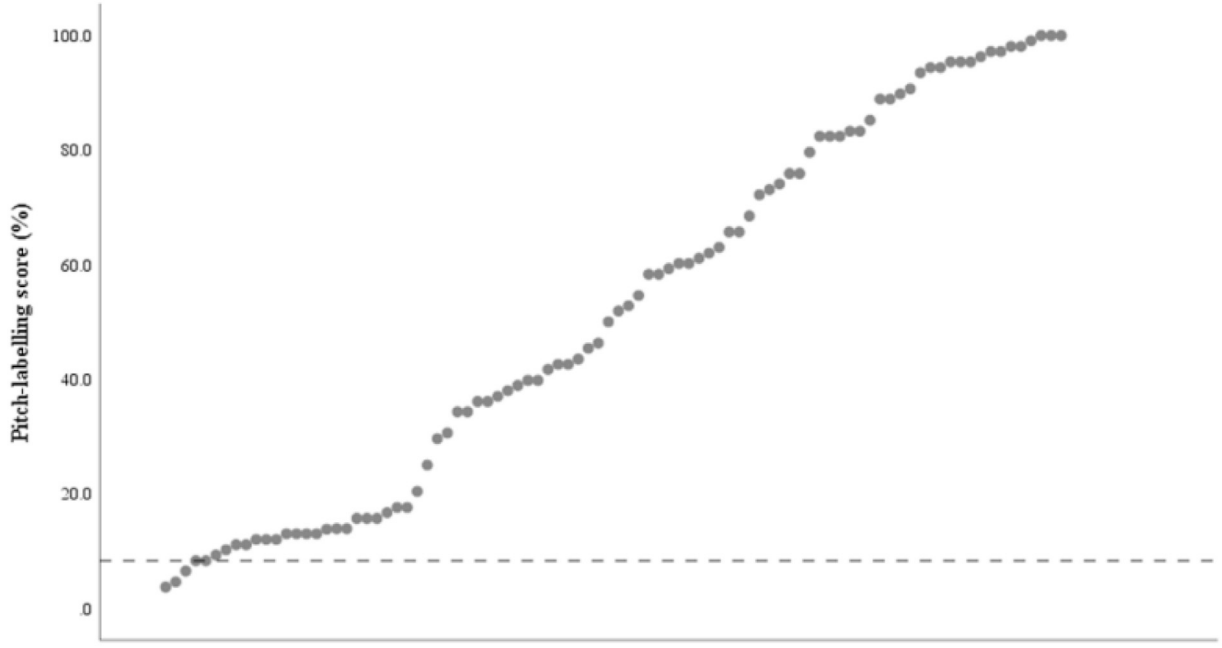

Fig. 1. Pitch-labeling scores (% correct answers). The chance level is indicated by the dotted line (8.3%).

size = 2 × 2 × 2 mm^3 (matrix 112 × 112 pixels, 76 slices, transverse orientation). Additionally, six non-diffusion-weighted volumes were acquired to correct for echo-planar imaging-related geometrical distortions in anterior and posterior directions. All technical parameters of those six non-diffusion-weighted volumes were identical with those of the reference volume (non-diffusion-weighted) of the actual DTI sequence, except that for three volumes the readout direction was posterior-to-anterior and for the other three volumes the readout direction was anterior-to-posterior.

All preprocessing steps were fully automated using the diffusion MRI tools of the FMRIB Software Library (FSL; version 6.0, https://fsl.fmrib.ox.ac.uk/fsl/fslwiki) (Smith et al., 2004). First, the TOPUP tool (https://fsl.fmrib.ox.ac.uk/fsl/fslwiki/topup) was applied to the six non-diffusion-weighted volumes to correct for distortions of the susceptibility induced field. Second, the output from TOPUP was fed together with the DTI volumes into the EDDY tool (https://fsl.fmrib.ox.ac.uk/fsl/fslwiki/eddy), which allows correction for subject's movements and eddy current-induced distortions. These preprocessed DTI data were then used for tract-based spatial statistics (TBSS) analyses.

2.2.1. Extraction of regions of interest

In order to restrict the statistical analyses of the TBSS data to perisylvian regions, we created a binary mask. Regions of interest (ROIs) were drawn from the Harvard-Oxford Cortical Structural Atlas (https://fsl.fmrib.ox.ac.uk/fsl/fslwiki/Atlases) as implemented in FSLVIEW (https://fsl.fmrib.ox.ac.uk/fsl/fslwiki/FslView). The following bilateral ROIs were selected based on the AP literature as well as on theoretical models of AP (Burkhard et al., 2019; Jäncke et al., 2012; Keenan et al., 2001; Loui et al., 2012, 2011; Schlaug et al., 1995; Schulze et al., 2009; Wengenroth et al., 2014): PT, PP, HG, as well as anterior and posterior divisions of the STG and MTG (Table 1). To obtain a binary mask that can be used for statistics with the RANDOMISE tool (see below), all 14 ROIs (unthresholded) were summed up.

2.2.2. Voxel-wise analysis of the fractional anisotropy data

Voxel-based analyses of the FA data were performed using TBSS (Smith et al., 2004), and the FDT toolbox (Behrens et al., 2003), which are both parts of the FSL library. To exclude non-brain tissue from further analyses, BET was applied to the non-diffusion-weighted images. Furthermore, the diffusion tensor model was fitted at each voxel using DTIFIT. Afterward, the TBSS steps were applied to the data. (1) FA data were prepared by using the –preproc option. (2) Nonlinear registration was applied to align the FA images to the high-resolution FMRIB58_BA standard-space image provided by FSL. (3) Using the –postreg option, the FA images of all subjects were affine-aligned to the 1 × 1 × 1 mm MNI152 space. A skeleton was created by taking the mean of all FA images. (4) A threshold of 0.2 was applied to the mean FA skeleton image, which resulted in a binary mask. This binary mask contained the information of the voxels that were used in all successive processing steps. Finally, FA images of all subjects were projected onto the mean FA skeleton. This procedure resulted in an image file that contained the projected mean FA skeleton data (4D). The processed data were then subjected to non-parametric permutation statistics (RANDOMISE tool, see below).

Table 1
Coordinates of the regions of interest (ROIs). The anatomic regions refer to the nearest-located cortical structures of the investigated white matter. For each ROI, the center of gravity is indicated with standard Montreal Neurological Institute coordinates (X, Y, Z). L = left hemisphere, R = right hemisphere.

Anatomic region	Hemisphere	MNI coordinates		
		X	Y	Z
Heschl's gyrus	L	−48	−18	5
	R	50	−16	6
Planum temporale	L	−54	−29	14
	R	56	−25	16
Planum polare	L	−48	−8	−4
	R	50	−6	−2
Anterior middle temporal gyrus	L	−58	−7	−20
	R	57	−4	−23
Posterior middle temporal gyrus	L	−59	−27	−13
	R	59	−22	−13
Anterior superior temporal gyrus	L	−56	−6	−9
	R	57	−3	−10
Posterior superior temporal gyrus	L	−57	−28	4
	R	59	−23	3

Table 2
Descriptive statistics of the demographic and behavioral variables. Mean, standard deviation, and range are depicted. For sex and handedness, the absolute frequencies are shown.

Measures (N = 90)			
Sex (female/male)	45/45		
Handedness (right/left/ambidextrous)	79/7/4		
	Mean	Standard deviation	Range
Age (years)	26.8	4.78	18–39
Training onset[a] (years)	6.29	2.42	1–15
Musical training[b] (hours)	1.44	1.13	0.14–6.59
Musical aptitude[c]	65.1	6.42	45–77
Pitch-labeling score (%)	51.75	32.1	3.7–100
Cognitive capability[d]	126.62	31.53	20.83–198.68

[a] Age of musical training onset.
[b] Estimation of the cumulative number of training hours across lifespan (units are given in 1 × 10^4).
[c] Total score of the AMMA-test.
[d] Total score of the KAI-test.

2.3. Statistical analyses

For an overview of the surveyed behavioral measures, descriptive statistics are provided. Because no group classifications were conducted, means, standard deviations and variable ranges were calculated.

To reveal correlations between pitch-labeling scores and FA within AP related WM regions, the 4D skeletonized FA images were fed into voxel-wise statistics using RANDOMISE (Winkler et al., 2014) that applies nonparametric permutation testing. The null distribution was built upon 5000 permutations. FA clusters that correlated with the pitch-labeling score were identified by the threshold-free cluster enhancement method. Furthermore, family-wise error (FWE) correction was applied to the data. To determine the labels of the brain areas that showed significant correlations with the pitch-labeling scores, the Harvard Oxford cortical structural atlas was applied. Only the labels with the highest probabilities are reported. For reasons of simplicity, we refer to the nearest-located cortical structures although the underlying WM was investigated. For visualization purposes, the *fill* command of TBSS was used to make the clusters graphically more visible.

For the voxel-wise TBSS analysis of the FA maps, effect sizes were reported. However, it must be noted that the computation is based on clusters that have already been identified as significant, resulting in an overestimation of the true effect (Kriegeskorte et al., 2010). All coordinates are reported in the standard Montreal Neurological Institute (MNI) space. To show the specificity of the results, a whole-brain analysis of the FA data is reported in the supplementary material (Table S1). The significance threshold for the analyses was set to $\alpha = 0.05$. Furthermore, to show results exceeding the main effects, the analysis was also conducted with a more liberate significance threshold ($\alpha = 0.20$, corrected for multiple comparisons).

3. Results

3.1. Behavioral data

Descriptive statistics of the variables age, musical training onset, estimated number of cumulative training hours across lifespan, musical aptitude, pitch-labeling score and cognitive capability are reported in Table 2. Furthermore, frequency distributions are given for the characteristics of sex and handedness.

3.2. Results of the FA analyses

Voxel-wise analyses revealed a positive correlation between FA values and AP proficiency in a left-sided perisylvian cluster. This cluster (99 voxels in size, $p = 0.024$, $r = 0.397$, x/y/z = −39/-40/13, FWE corrected) comprised the WM underlying the left-sided PT (Fig. 2). According to the JHU white-matter tractography atlas (Mori et al., 2005), the significant cluster corresponds to the posterior branch of the left-sided SLF.

The correlation between the pitch-labeling scores and the mean FA values of the significant cluster of the WM underlying the left-sided PT ($r = 0.397$) is depicted in Fig. 3.

Furthermore, the analysis with a more liberal significance threshold of $\alpha = 0.20$ (FWE corrected) revealed four additional smaller clusters, which are, except one cluster, located in the left hemisphere (Table 3). The largest of these additional non-significant clusters is located in the WM underlying the left PP (cluster 2). Furthermore, the analysis revealed a second cluster in the left-sided posterior PP at the border to the anterior HG (cluster 3). The only cluster located in the right hemisphere was also found in the WM underlying the PP (cluster 4). The smallest cluster contains eight voxels and was found in the insular cortex (cluster 5).

4. Discussion

The aim of the present study was to identify WM properties (here FA) of perisylvian brain areas that are associated with AP ability using a correlational approach. So far, only group differences between absolute and non-absolute listeners have been investigated. However, the intermediate levels of AP performance have almost been neglected. In this study, we examined whether possible gradual differences in pitch-labeling are also related to gradual differences in specific anatomical features of the WM. Based on previous studies, we hypothesized that FA would be higher in musicians with better pitch-labeling abilities. In line with this reasoning, we identified that FA values of the WM underlying the left PT positively correlated with AP ability.

Increased FA values are thought to reflect increased myelin integrity and WM organization (Schmithorst et al., 2002; Schmithorst and Wilke, 2002). Such an optimization of microstructural WM properties could increase the velocity of impulse propagation between different patches of cortex and lead to a higher functional efficiency of information processing. With this in mind, one can argue that the more the PT and here particularly the left-sided part is efficiently connected to other brain regions within the auditory and non-auditory cortex, the better the AP ability is. Accordingly, previous studies have highlighted the importance of the PT for AP (Gaser and Schlaug, 2003; Keenan et al., 2001; Luders et al., 2004; Schlaug et al., 1995; Wilson et al., 2009). The PT has been proposed to be a "computational hub" for higher-order auditory processing. In order to be able to perform this function, the PT segregates the signals received from the primary auditory cortex into different spectro-temporal patterns using something similar to an independent component analysis (Griffiths and Warren, 2002; Hall and Plack, 2009). These signals are conveyed to higher brain areas for further processing. The spectro-temporal patterns relate to sound objects and their localization in space and are processed in the corresponding brain areas. Regarding the ability of AP, it could be that the PT allocates the different pitch chromas contained in the signal to different object patterns and forwards the information to higher-order auditory processing areas for further processing, which could enable the later occurring labeling of the different chromas. In addition, the PT is suggested to be involved in the processing of elementary pitch properties and pitch salience (Griffiths and Warren, 2002; Hall and Plack, 2009), which fits well with the possible role of the PT as a computational hub. Thus, it might be possible that the superior connection of this important hub subserves the establishment of AP ability.

As shown in Fig. 2, the WM underlying the PT seems to be part of the SLF. The SLF is a fiber bundle that connects temporal with frontal brain regions and is especially involved in speech processing (Oechslin et al., 2010). Furthermore, the SLF plays a role in music processing. Bengtsson et al. (2005) found a positive correlation between FA values in the SLF and the estimated hours of music practice. In accordance with the dual-stream model of language perception and production (Rauschecker and Scott, 2009) the SLF is part of the postulated postero-dorsal stream. Interestingly, the authors suggest that the dorsal processing stream originates from the PT or so-called pST (posterior superior temporal) region and that this brain area is involved in the spectro-temporal processing of acoustic sounds. Furthermore, Rauschecker and Scott (2009) pointed out that the postero-dorsal stream is also associated with "doable" templates, which representations are suggested to originate within the PT (Rauschecker and Scott, 2009; Warren et al., 2005). "Doable" should be interpreted in the context of the forward mapping mentioned in Rauschecker and Scott (2009). In particular, a heard sound is processed along the antero-ventral stream and then the information is transformed into a motor-action representation in the postero-dorsal stream, resulting in an efference copy for reproducing a specific sound. The postero-dorsal stream comes into play when a sound is produced and its production is monitored for the correct outcome. This interplay between forward and inverse mapping is not restricted to language. Halwani et al. (2011) found differences in the left dorsal pathways of singers, which they explained with the singers training requiring the forward and inverse mapping processes mentioned above. Hence, it could be that the ability of highly skilled APPs, e.g. to label and produce specific tones without reference, is modulated by the PT as part of the auditory postero-dorsal stream. However, increased FA values in the left-sided SLF in participants with higher AP abilities in the present study would

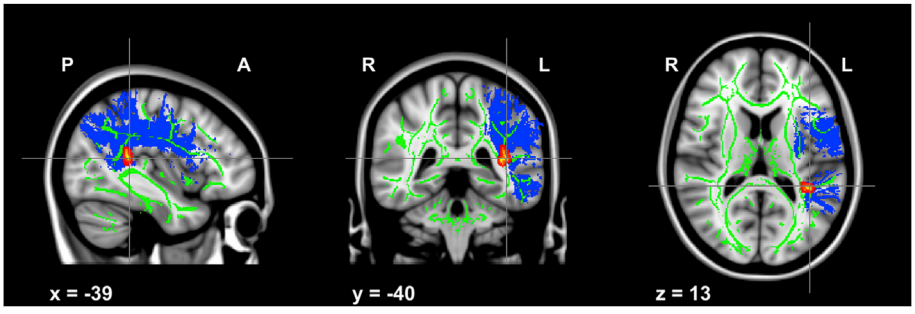

Fig. 2. Results of the voxel-wise fractional anisotropy analyses. A cluster (red) located beneath the left planum temporale positively correlated with the pitch-labeling scores. The probabilistic tract structure of the left-sided superior longitudinal fasciculus is shown in blue. The superimposed crossline indicates the maximal values within the cluster as well as the corresponding Montreal Neurological Institute coordinates. Images are shown according to the radiological convention. A = anterior, P = posterior, L = left, R = right.

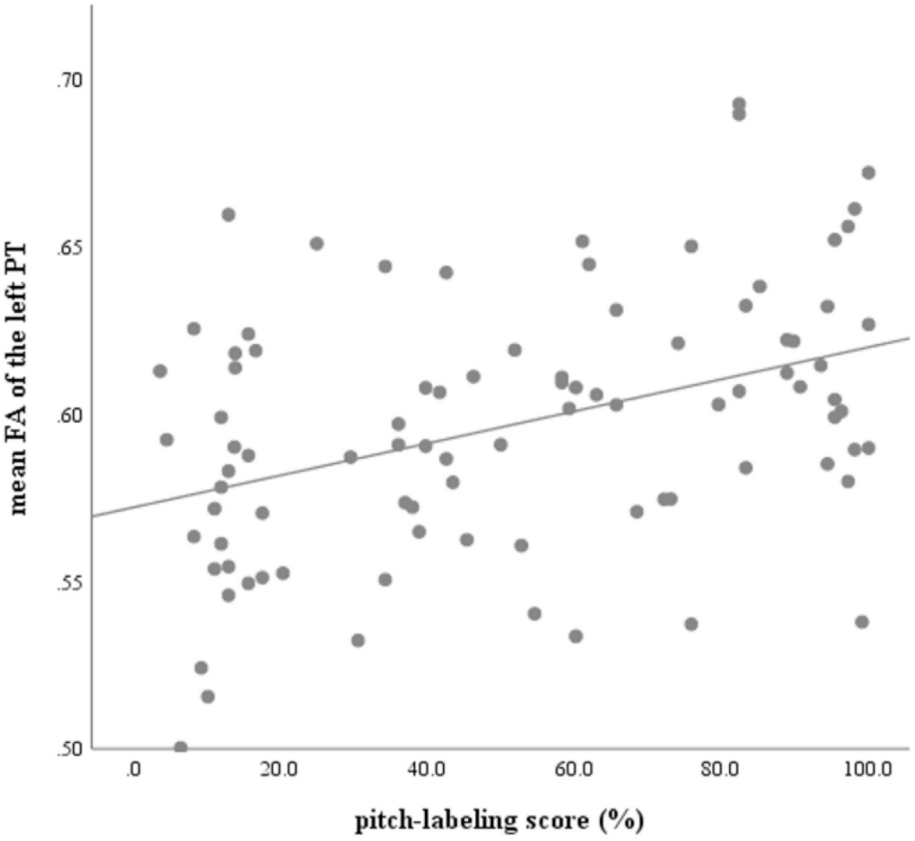

Fig. 3. Correlation between the mean fractional anisotropy values of the significant cluster of the white matter underlying the left-sided planum temporale and the pitch-labeling scores (r = 0.397).

Table 3
Results of the voxel-wise analysis of the fractional anisotropy data with a significance threshold of α = 0.20 (family-wise error corrected). As expected, the cluster size of the significant cluster increases with a more liberal threshold.

Cluster number	Cluster size (voxel)	p-value	MNI			Label[a]
			X	Y	Z	
1	301	.024	−39	−40	13	Planum temporale
2	75	.121	−43	−21	−8	Superior temporal gyrus/planum polare
3	34	.166	−37	−25	−1	Planum polare/ insular cortex
4	10	.153	49	−11	−7	Planum polare
5	8	.198	−37	−18	−8	Insular cortex

[a] Labels were determined with the Harvard Oxford cortical structural atlas. The labels with the highest probabilities are depicted.

confirm earlier findings from our group that showed a larger left-sided FA asymmetry in the SLF of APPs (Oechslin et al., 2010). Oechslin et al. (2010) found three clusters within the left-sided SLF that correlated with the performance in an AP test. One of the three clusters (x/y/z = −42/-50/4) lies in the vicinity of the cluster identified in the present study (x/y/z = −39/-40/13). The authors associated two of the clusters with the ability of APPs to relate a heard tone to their own instrument. Accordingly, the authors assumed that those two parts of the SLF underlie cortical regions that are important for the development of AP.

4.1. Future perspectives

In the present work, musicians with higher AP abilities revealed increased left hemispheric FA values in the PT. In general, the STG/superior temporal sulcus is thought to be involved in the long-term representation of pitch, pitch perception, categorization, and the identification of different auditory objects (Belin and Zatorre, 2000; Binder et al., 2000; Loui et al., 2012; Schulze et al., 2009; Wilson et al., 2009). However, previous studies showed a heterogeneous picture concerning the role of the STG in AP. For example, the anatomical study of Dohn et al. (2015) revealed an increased cortical thickness in the bilateral STG for APPs when compared to RPPs. In line with previous studies (Keenan et al., 2001; Luders et al., 2004; Schlaug et al., 1995), the authors reported a left lateralization of the pSTG for APPs. Furthermore, Loui et al. (2011) found enhanced FA for APPs in the bilateral WM pathways connecting the STG with the MTG. The same authors also reported a positive correlation between the left-sided tract volume and AP performance. A left-lateralization was also reported in the study by Oechslin et al. (2010), which showed increased FA in the left-sided SLF. Otherwise, Kim and Knösche (2016) revealed increased myelination in the right-sided PP in APPs. Furthermore, a positive correlation between the anterolateral part of the right-sided STG and a frequency discrimination threshold was found. A functional study by Schulze et al. (2009) showed a bilateral activation pattern in the STG for both, AP and non-AP musicians. A significant group difference was reported in the middle part of the left-sided superior temporal sulcus, and a trend towards significance for an increased bilateral activation in the STG for APPs. Increased small-world network parameters were found in the left-sided STG for APPs by Loui et al. (2012). A study by Wengenroth et al. (2014) highlighted the role of the right-sided perisylvian brain (including the dorsal STG) for APPs. Furthermore, a recently published EEG study from our lab (Burkhard et al., 2019) also revealed the relevance of the right perisylvian brain for APPs during attentive tone listening.

However, the studies mentioned above differed in terms of methods and paradigms used, which might explain a considerable amount of the heterogeneous results. The findings mentioned above might highlight some aspects of a wider network that is required for AP processing

involving both hemispheres: the left-sided brain could be presumably involved in labeling processes while bilateral or right-hemispheric perisylvian brain areas are recruited for perceptual aspects of AP processing, such as tone categorization. However, it is worth considering that the correlations found in this study relate more to labeling than to AP in general. This, due to the fact that the pitch-labeling test performance used for the calculations of the correlations relies on labeling a given tone correctly. In accordance, the left-hemispheric correlations between tract volume of the pathway connecting the STG with the MTG (Loui et al., 2011) and FA of the SLF (Oechslin et al., 2010) with AP performance can also been seen in that light. It could be that a left-sided perisylvian network might support the quick and effortless labeling process in APPs, which is, among others, reflected by increased FA. In accordance with this, Meyer et al. (2014) provided evidence for a relationship between increased cortical surface areas (CSA) and the corresponding WM of left-sided auditory related fields. The authors suggested that increased CSA and thinner cortex in auditory related areas could reflect the specialization of the left hemisphere for rapid temporal processing. Enhanced CSA could emerge from a wider spacing of microcolumns, which could lead to an advantage for the left hemisphere for processing temporal features of auditory stimuli (Hutsler, 2003). This view is reconcilable with previous models that suggested an advantage of left perisylvian brain areas for temporal processing (Poeppel, 2003; Zatorre et al., 2002). However, the authors (Meyer et al., 2014) suggested that thinner cortical thickness could be driven by enhanced myelination during brain development whereby gray matter is substituted by WM. From this perspective, the general basis of AP could be set during brain development.

However, future studies should incorporate both functional and anatomical methods and ideally also different paradigms (for example active and passive listening) to better elucidate the role of specific brain regions in different functions related to AP processing.

4.2. Limitations

A limitation of the present study could be that the pitch-labeling test was completed at home and not under strictly controlled laboratory conditions. It might be possible that the particular test procedure exerts an influence on the measured AP scores. However, unpublished studies in our lab revealed strong correlations between AP test scores obtained with online tests and under strict laboratory control. So far, there is no consensus about how to evaluate the AP ability reliably. Furthermore, previous studies differed with regard to the administration and scoring systems of the AP-tests that were used. Moreover, the stimulus material varied, for example, in type (sine tones, sampled instruments, etc.), length, loudness, and number of trials. As already mentioned in the introduction, there are various degrees of AP accuracy. Therefore, stimulus type, response accuracy and latency could provide valuable information to disentangle different labeling strategies. For example, already Bachem (1937) mentioned that some musicians possess a single intern reference tone (a specific tuning tone or the deepest tone one is able to sing) that is used to calculate the label of the target tone. This strategy would be reflected by longer reaction times as the computation needs more time than a labeling that is absolute and effortless. Furthermore, no standard scoring and analyzing method for the AP test evaluation is available. In some studies, only exact responses were counted as correct (Burkhard et al., 2019), whereas in other studies half-points were given for semi-tone deviations to the target tone (Loui et al., 2011). Both scoring strategies have consequences with respect to the distribution of test performance, as described by Bermudez and Zatorre (2009). However, it is not clear so far which would be the most valid technique to identify AP musicians. This will be an endeavor for future research. In conclusion, a progress in the field of AP research would be to reach a common agreement on the above-mentioned parameters in order to enable a more adequate and consistent evaluation of AP.

5. Conclusions

Based on the findings in the present study we suggest (as we and others did so previously) that the left PT and the fiber tracts connecting this hub with surrounding areas are related to AP. Furthermore, we provided evidence showing that FA values in the WM underlying the PT are gradually pronounced depending on AP skills.

Data availability statement

Raw data are not publicly available. Data are however available from the authors upon reasonable request and with permission of the participants of the current study.

Author contributions statement

AB made contributions to the interpretation of the results, performed statistical analysis, and drafted the manuscript. JH made contributions to the design, performed statistical analysis, made contributions to the interpretation of the results, and critically revised the manuscript. SE made contributions to the interpretation of the results, and critically revised the manuscript. LJ made contributions to the design and interpretations of the results, and critically revised the manuscript. All authors approved the final manuscript.

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuroimage.2020.116590.

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